Physics of B_s Mesons and Bottom Baryons at the Tevatron

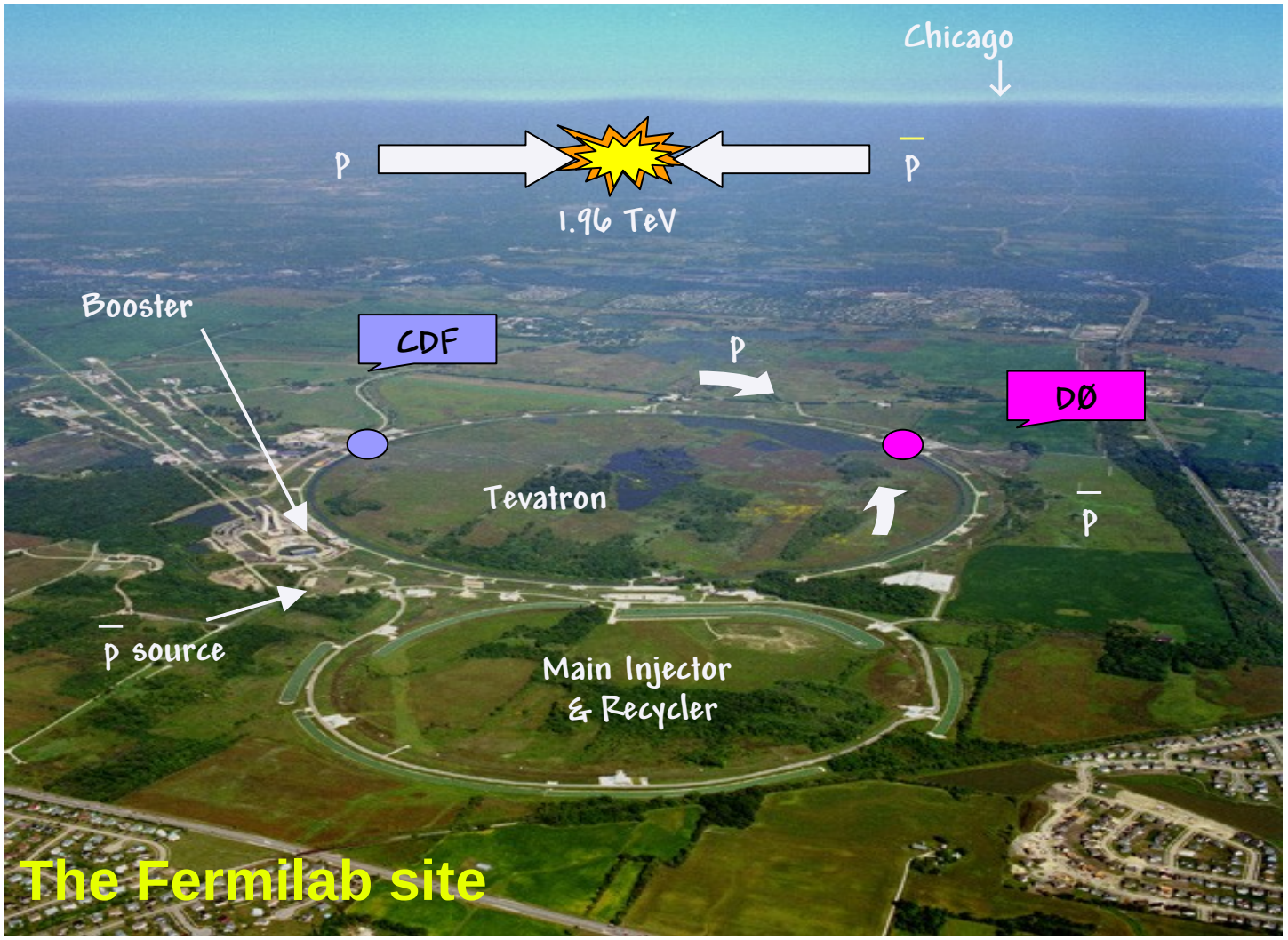
Manfred Paulini

Carnegie Mellon University

CIPANP 2009
San Diego, CA

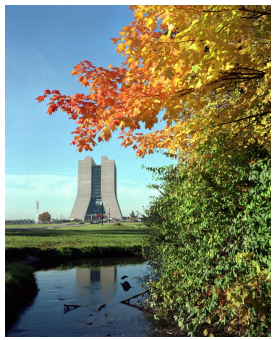
May 26 - 31, 2009

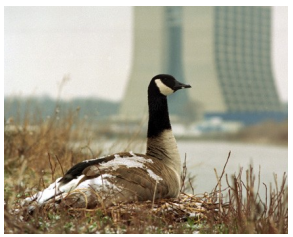
Fermilab



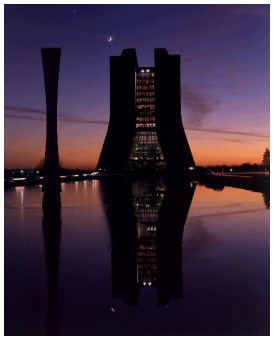
The Fermilab site







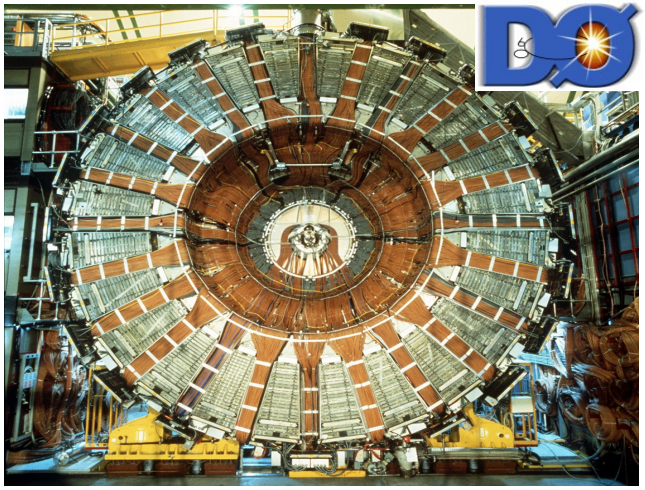


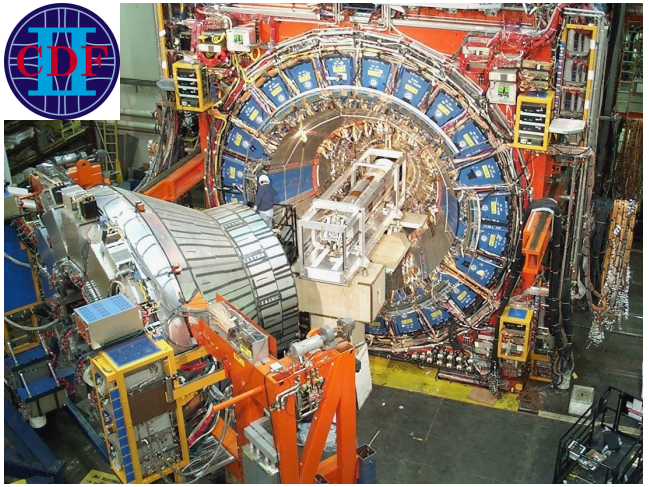



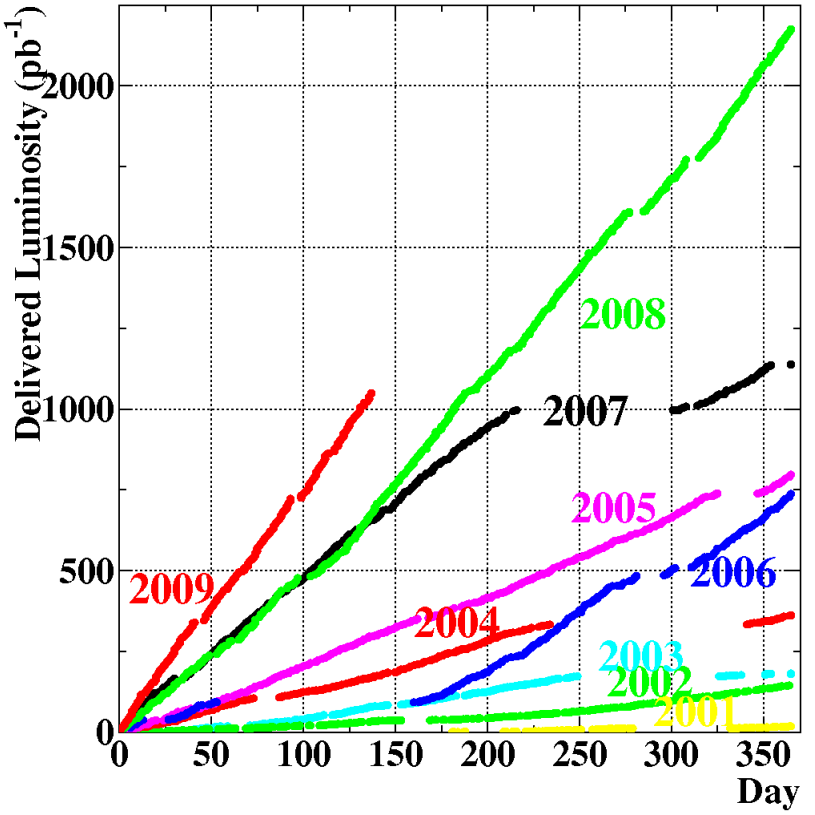
Exp. Equipment

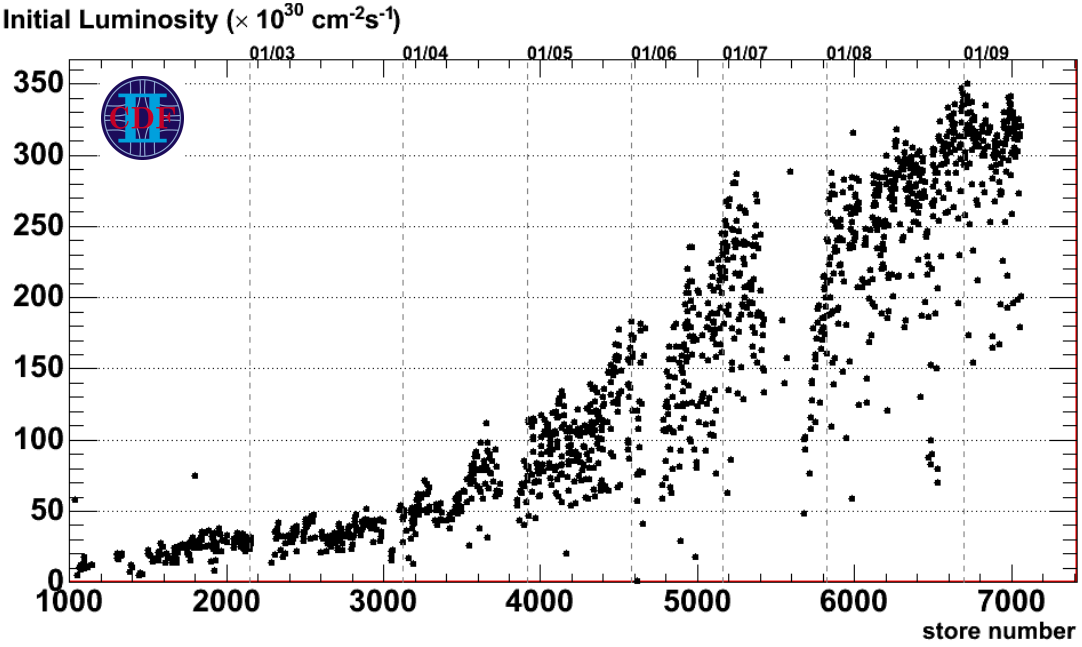
Tevatron is running well:

- ~6.5 fb^{-1} delivered, ~5.5 fb^{-1} on tape
- ~1-5 fb^{-1} used for analysis





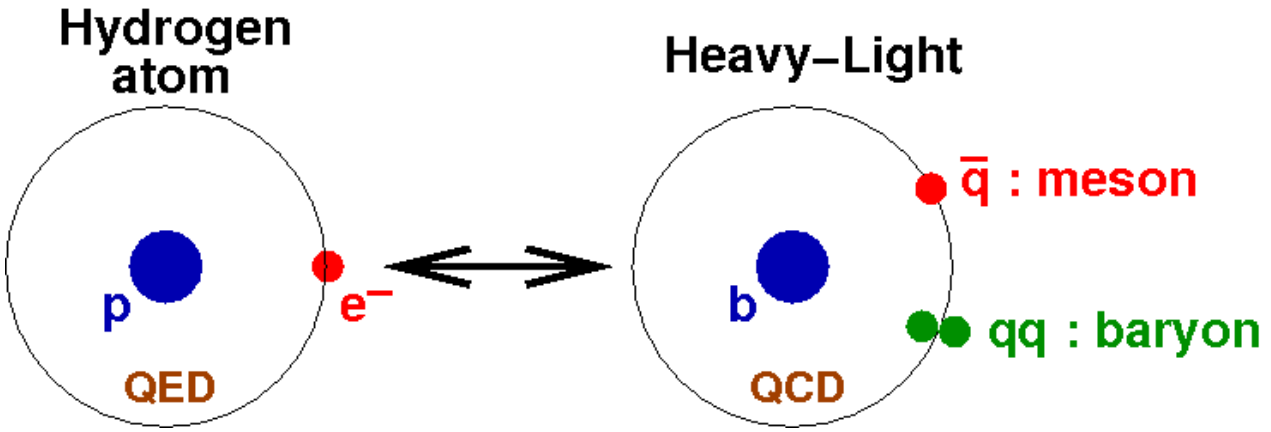




Motivation

Why study B hadrons?

From
hydrogen atom
to
B hadron
spectroscopy



- Heavy quark hadrons are the hydrogen atom of QCD
  => study of B hadron states = study of (non-perturbative) QCD
- Study of CKM mechanism provide precision tests of SM
  => Search for physics beyond SM through loop processes

Tevatron: $p\,\bar{p} \rightarrow b\bar{b}X$ (all B hadrons produced)

$\bar{B}^0 = |b\,\bar{d}\rangle,\ B^- = |b\,\bar{u}\rangle$ $\quad\quad$ $\Lambda_b^0 = |b\,d\,u\rangle,\ \Sigma_b^- = |b\,d\,d\rangle$

$\bar{B}_S^0 = |b\,\bar{s}\rangle,\ B_c^- = |b\,\bar{c}\rangle$ $\quad\quad$ $\Xi_b^- = |b\,d\,s\rangle,\ \Omega_b^- = |b\,s\,s\rangle$

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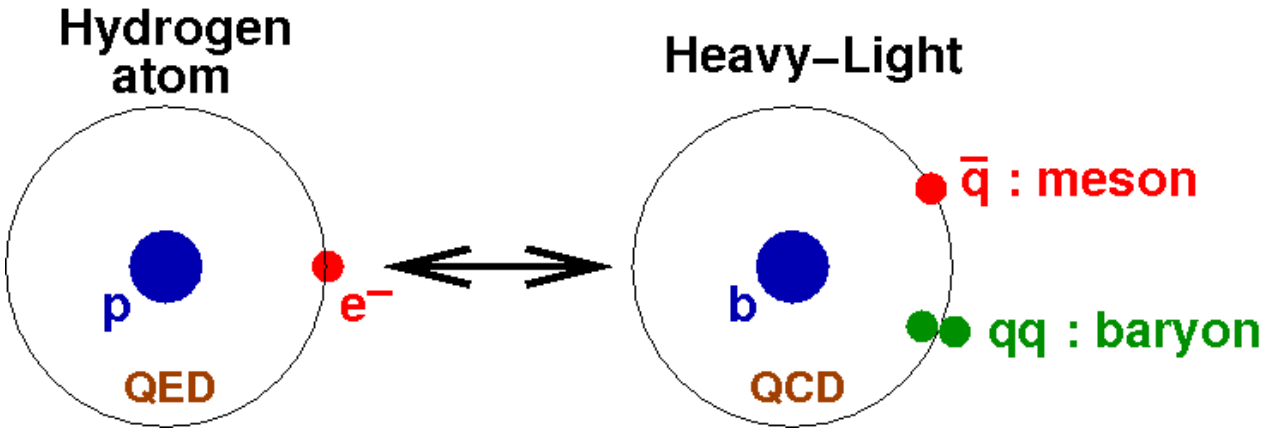

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B_s^0 Meson Physics

Neutral B_s^0 System

B_s^0 System: 2 flavour eigenstates: $B_s^0 = |\bar{b}s\rangle \;\; \& \;\; \bar{B}_s^0 = |b\bar{s}\rangle$

Time evolution of states governed by Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} = \underbrace{\left[\begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix}\right.}_{\text{mass matrix}} - \frac{i}{2}\underbrace{\left.\begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix}\right]}_{\text{decay matrix}} \begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix}$$

Mass eigenstates are admixture of B_s^0 flavour eigenstates:

$$|B_s^H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle \qquad |B_s^L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle \qquad \frac{q}{p} = \frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}$$

where $\Delta m_s = m_H - m_L \sim 2|M_{12}|$ **Oscillations between B_s^0 & $\bar{B}_s^0$**

$\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2\,|\Gamma_{12}|\cos(\phi_s)$ **Lifetime / width difference**

$\phi_s = \arg(-M_{12}/\,\Gamma_{12})$ **CP phase**

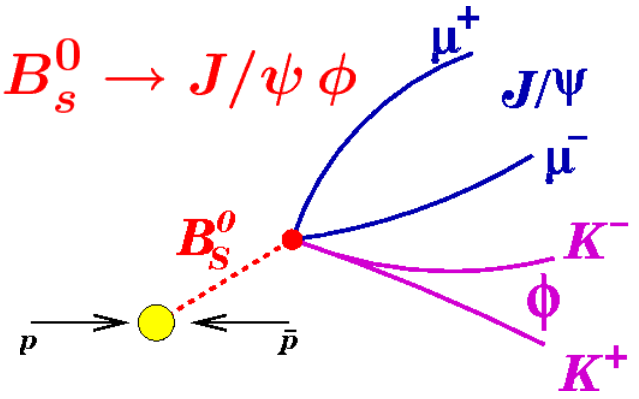
Assume no CP violation ($\phi_s^{SM} \sim 0.004$) => mass eigenstate = CP eigenstate

=> Γ_L ~ CP even (short lived) & Γ_H ~ CP odd (long lived)

Experimental observables describing system:

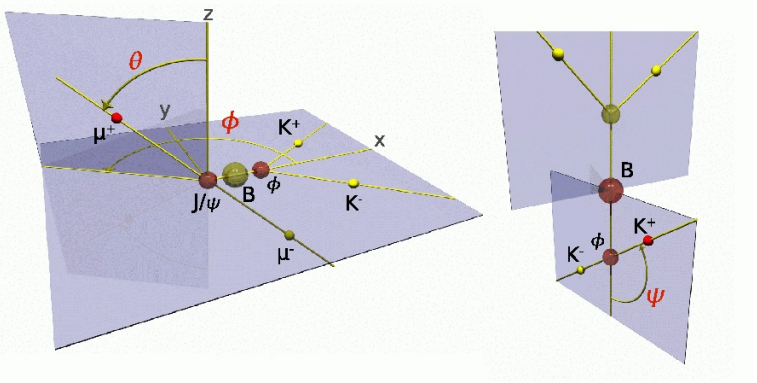
$m_H, m_L \Rightarrow \Delta m_s$, $\Gamma_s = (\Gamma_H + \Gamma_L)/2 = 1/\tau_s$, $\Delta\Gamma_s$, ϕ_s

CP Violation in B_s^0 -> $J/\psi\,\phi$

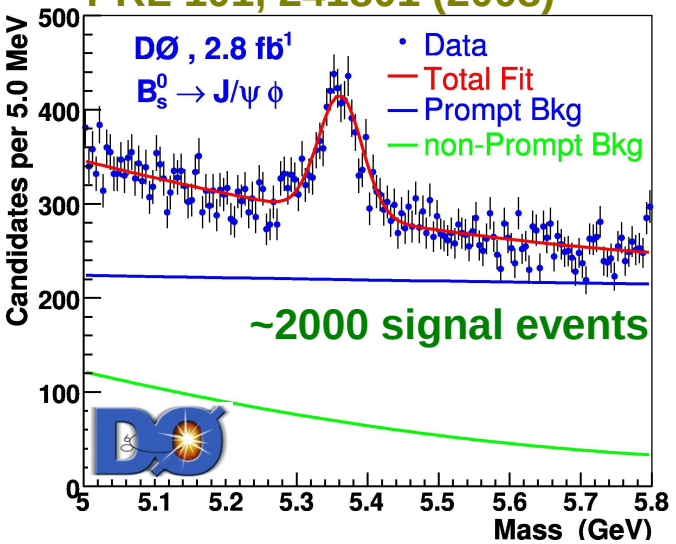


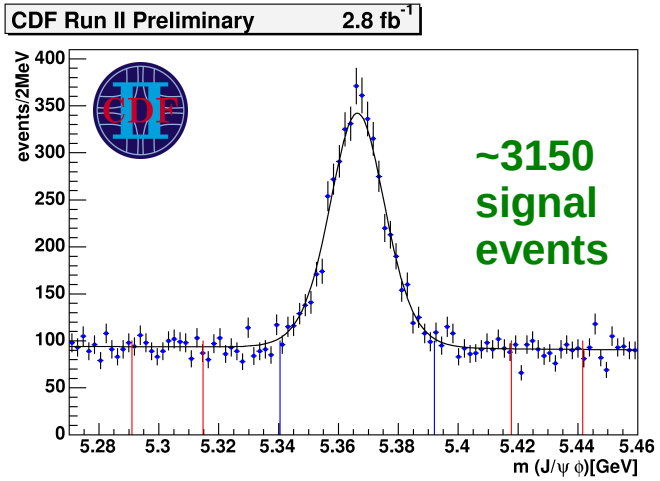
- **Status of analyses:**
  - D0: Result with 2.8 fb^{-1} published in PRL
  - CDF: Update to 1.3 fb^{-1} published result with 2.8 fb^{-1} for ICHEP'08
- Decay $B_s^0 \to J/\psi\,\phi$ (spin-0 -> spin-1 + spin-1) leads to 3 different angular momentum final states:
  - L=0 (s-wave), L=2 (d-wave) -> CP even
  - L=1 (p-wave) -> CP odd
- Use decay angular distribution in transversity basis $\vec{\rho} = (\cos\theta,\ \phi,\ \cos\psi)$ to disentangle CP states

=> mainly CP even



PRL 101, 241801 (2008)





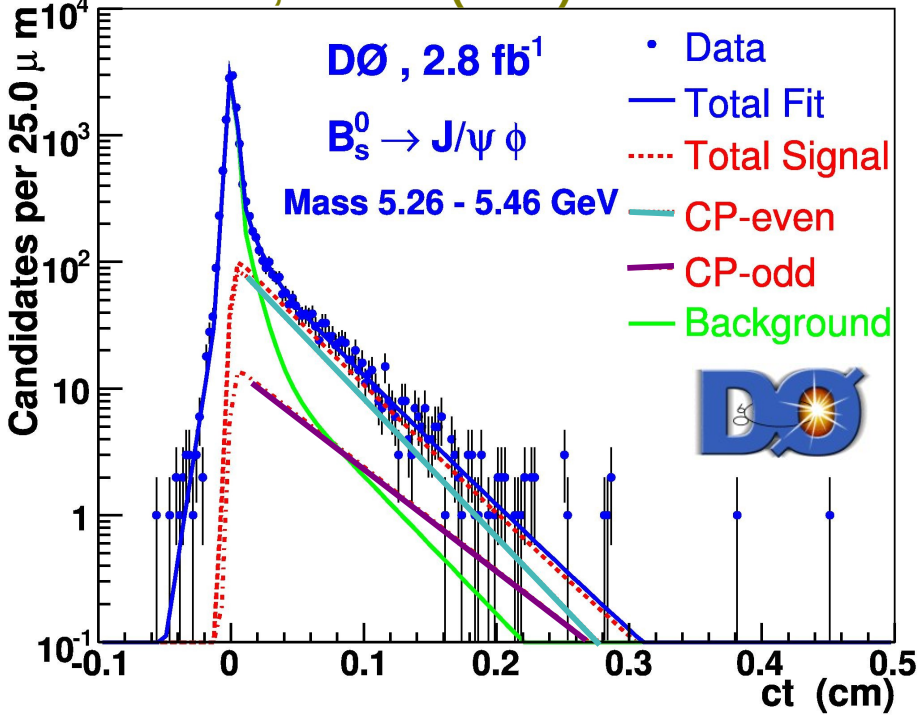
B_s^0 -> J/ψ φ Analysis

Results:

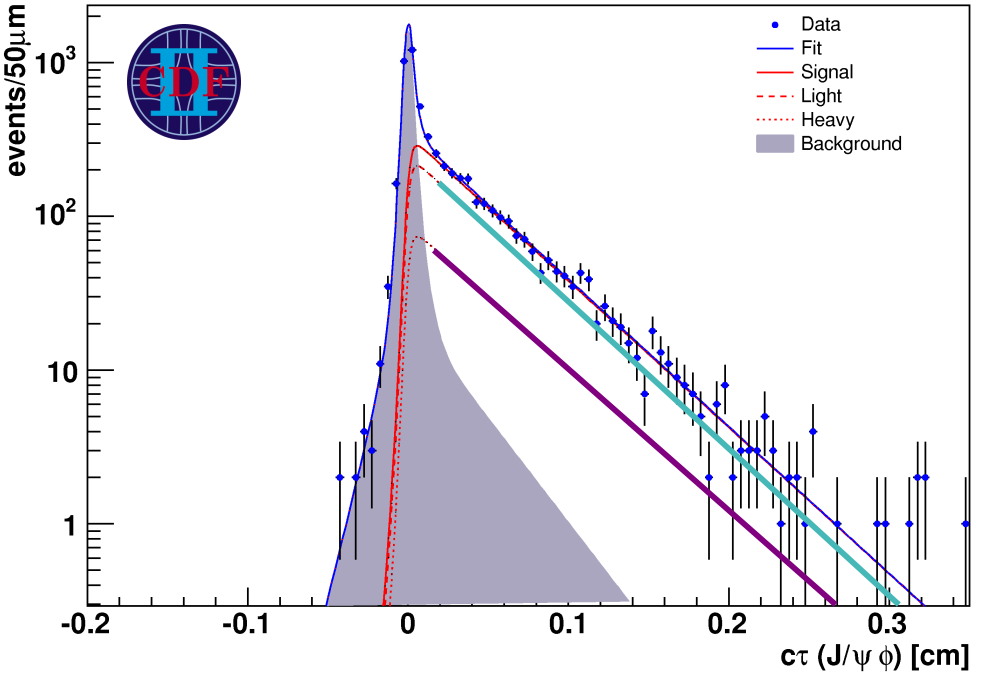
- **Measurement of lifetime and $\Delta\Gamma$**

CP even
CP odd

PRL 101, 241801 (2008)



CDF Run II Preliminary 2.8 fb^{-1}



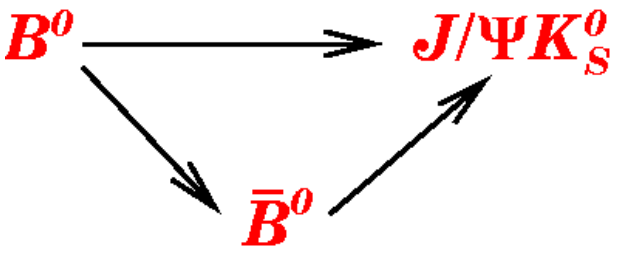
$\tau_s = 1/\Gamma_s = (1.52 \pm 0.06 \pm 0.01)$ ps
$\Delta\Gamma_s = (0.19 \pm 0.07 \pm 0.02)$ ps^{-1}

$\tau_s = 1/\Gamma_s = (1.53 \pm 0.04 \pm 0.01)$ ps
$\Delta\Gamma_s = (0.02 \pm 0.05 \pm 0.01)$ ps^{-1}

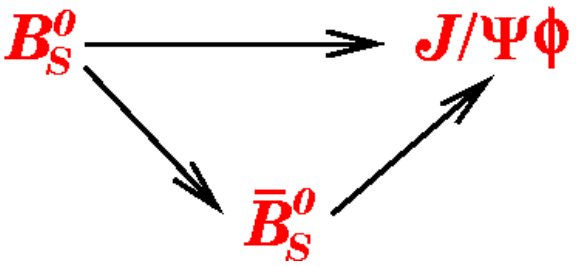
B_s^0 -> $J/\psi\,\phi$ Analysis

- With flavor tagging measure time dep. *CP* asym. => determ. β_s

  Analogy to measurement of CKM angle β in B^0 -> $J/\psi K_S^0$

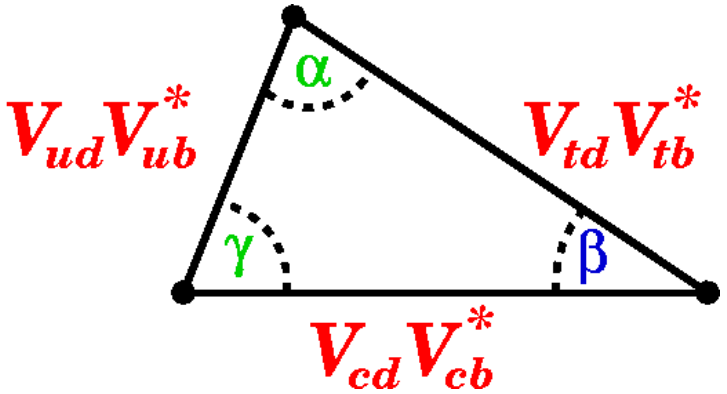


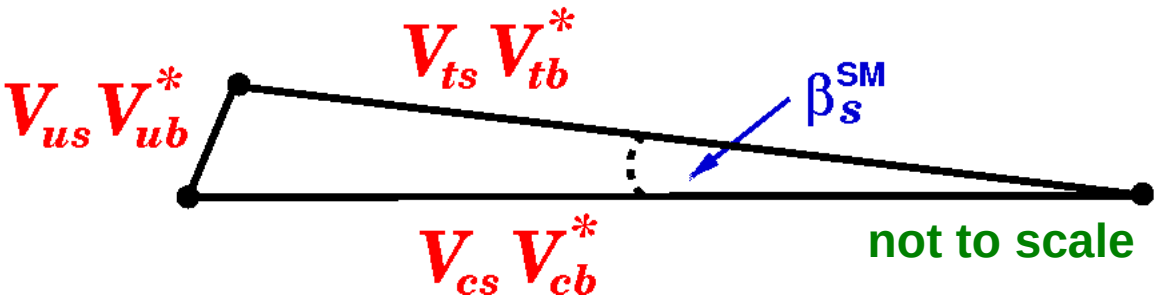
=> sin 2β



=> sin $2\beta_s^{SM}$

$$\beta_s^{\mathrm{SM}} = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$





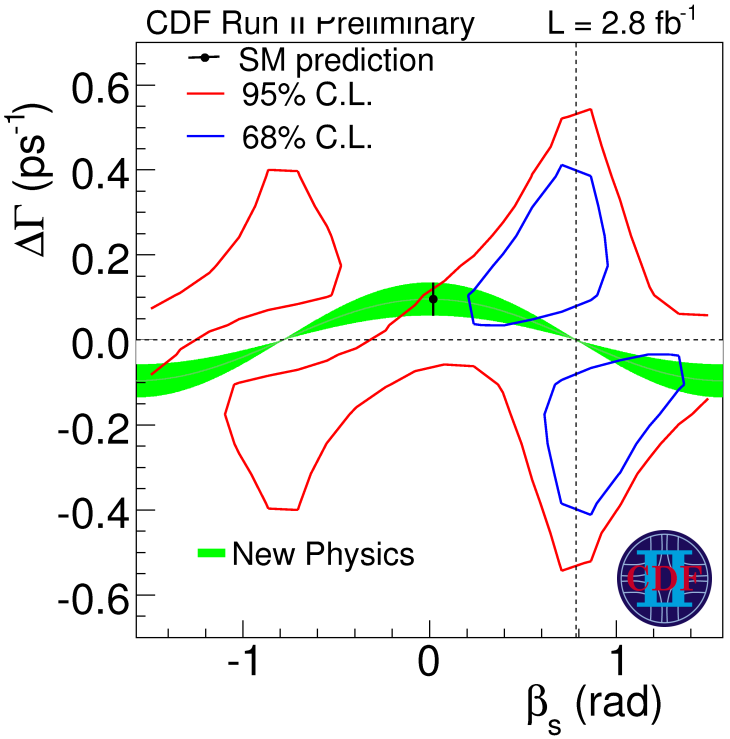
Expect β_s to be small in SM ($|\beta_s^{SM}| \approx 0.02$) - beyond current reach

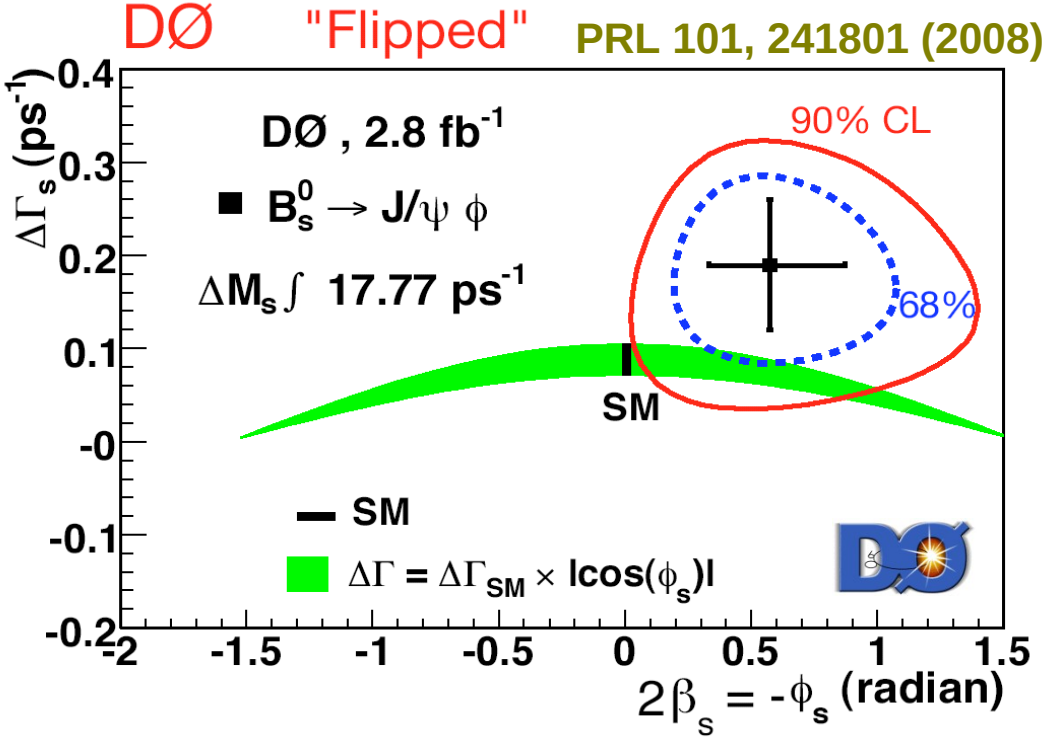
=> Current interest: Search for enhanced CP violation through new physics: $2\beta_s^{J/\psi\phi} = 2\beta_s^{\mathrm{SM}} - \phi_s^{\mathrm{NP}}$

CP Violation in B_s^0 -> $J/\psi\ \phi$

Current status:

- CDF prelim. (2.8 fb^{-1}) and D0 published (2.8 fb^{-1}) results
- Expressed as confidence regions in β_s-$\Delta\Gamma_s$ plane



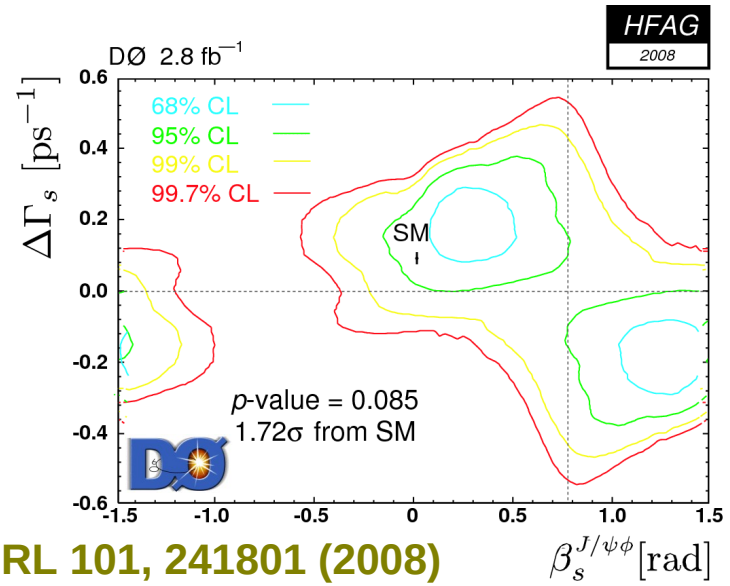


- p-value(SM): 0.07 (~1.8σ) Use external constraints on strong phases
- β_s in [0.28, 1.29] at 68% CL
- p-value(SM): 0.066 (~1.8σ)

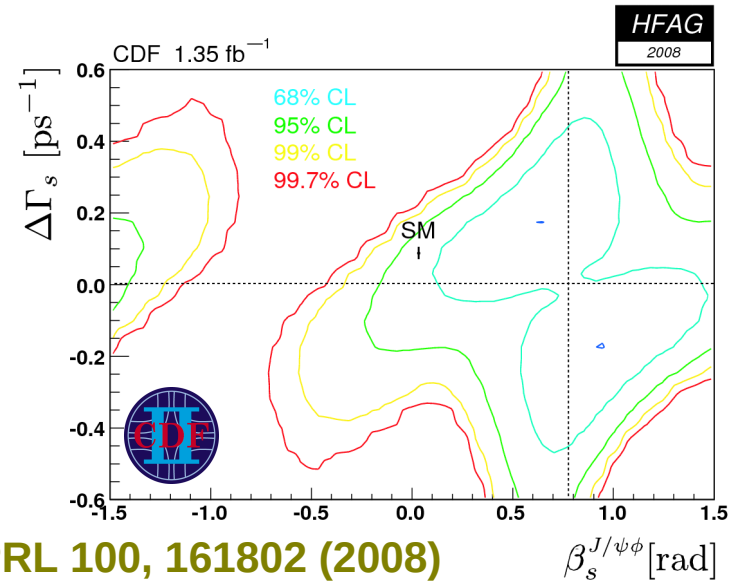
Mild inconsistency with SM (but in same direction)

CP Violation in B_s^0 -> $J/\psi\,\phi$

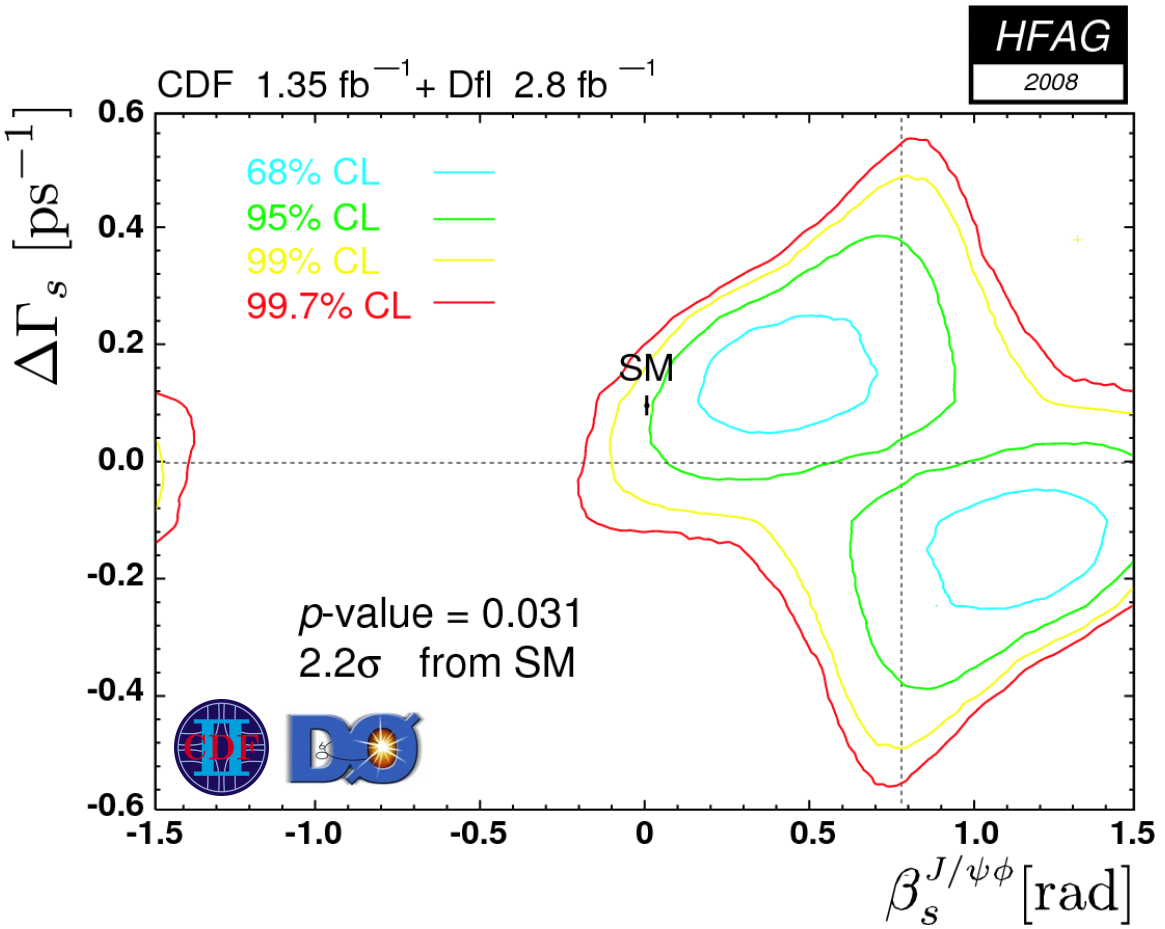
ICHEP08: D0 released data with no constraint for avg. with CDF



PRL 101, 241801 (2008)



PRL 100, 161802 (2008)



β_s in [0.14,0.73] or [0.83,1.42] at 90% CL

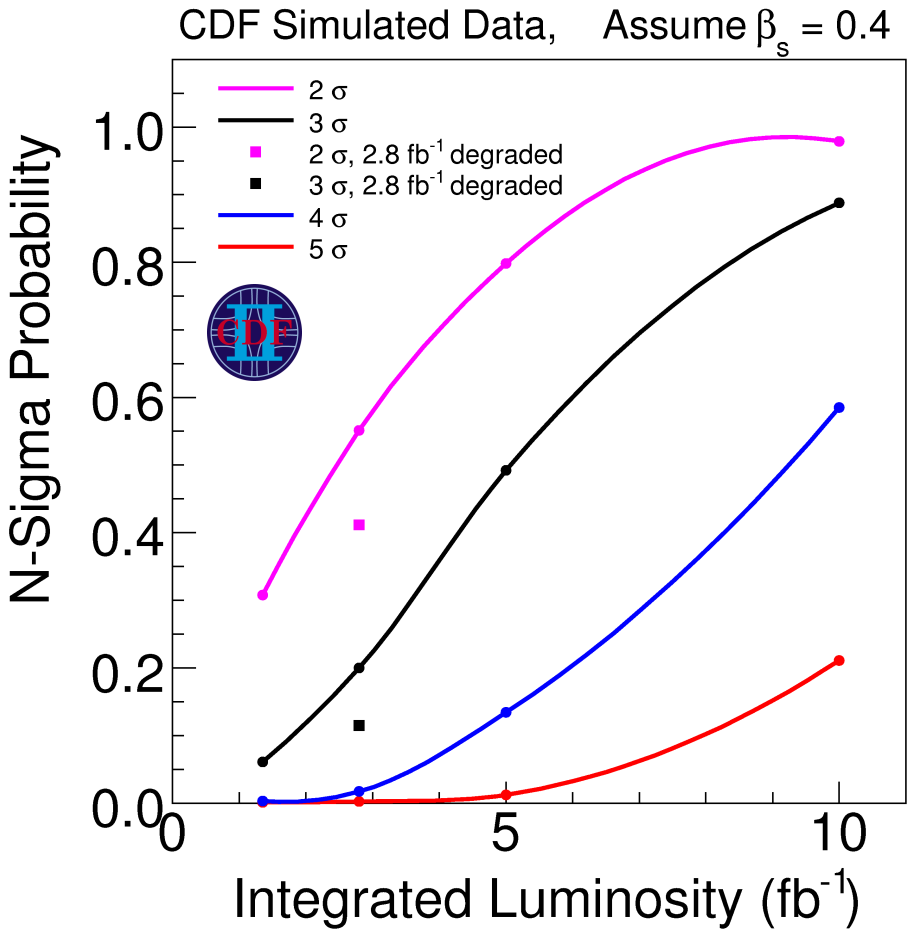
Combined p-value(SM): 0.031 (~2.2σ)

CP Violation in B_s^0 -> $J/\psi\ \phi$

Expect more to come:

- **Combination of both CDF & D0 2.8 fb^{-1} results in progress (TeV working group, unify uncertainties, combined fit)**
- **D0 update with 5 fb^{-1}**
- **CDF update with 4 fb^{-1}**

  => Summer 2009 ?



CDF expected sensitivity

Bottom Baryons

Σ_b - Ξ_b - Ω_b

Heavy B Baryons

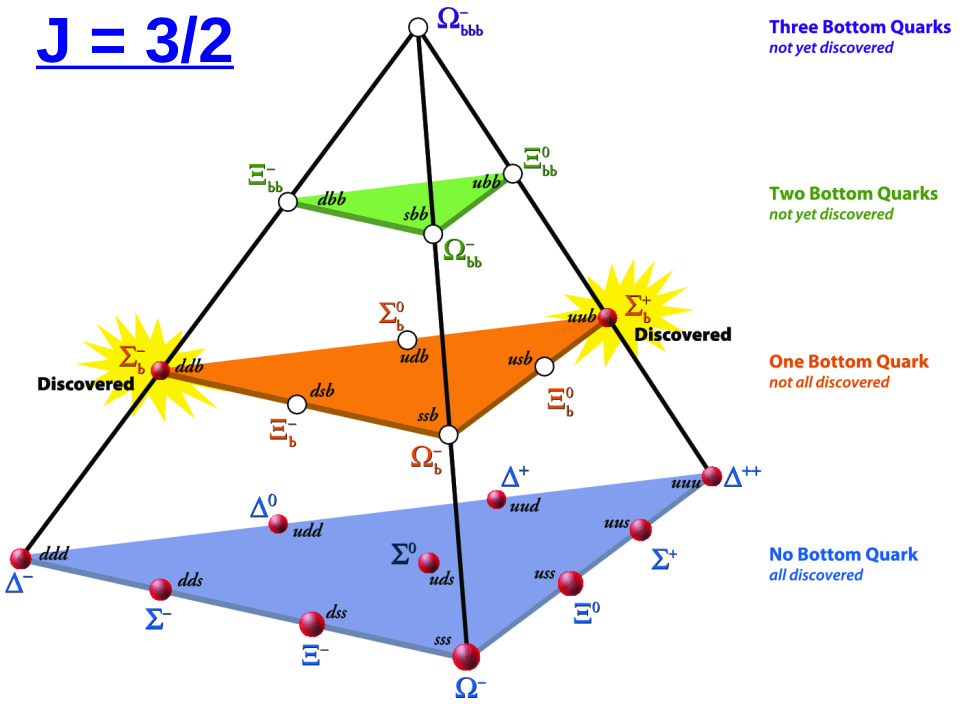
Motivation:

Until 2006 $\Lambda_b^0 = |b\,d\,u\rangle$ was only established *B* baryon

=> Search for

$\Sigma_b^- = |b\,d\,d\rangle$

$\Xi_b^- = |b\,d\,s\rangle,\ \Omega_b^- = |b\,s\,s\rangle$

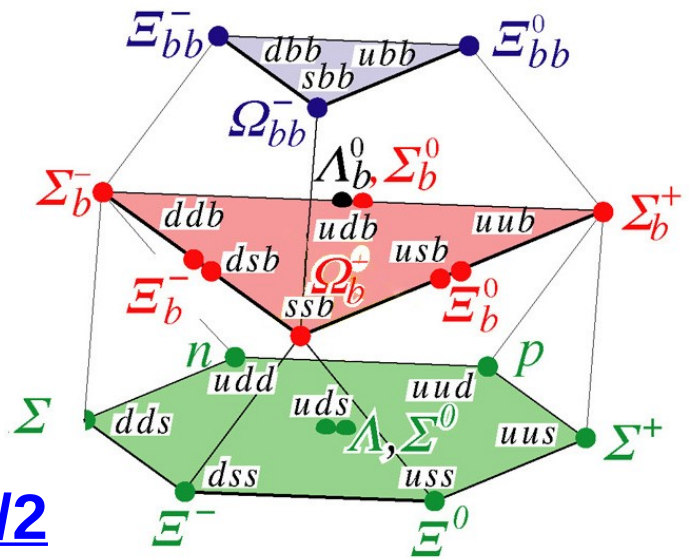


Example: Σ_b

Σ_b: $b\{qq\}$, $q = u,d$; $J^P = S_Q + s_{qq}$

= $3/2^+$ (Σ_b^*)

= $1/2^+$ (Σ_b)



H-atom: spin-spin interaction
= hyperfine splitting

Σ_b Baryon

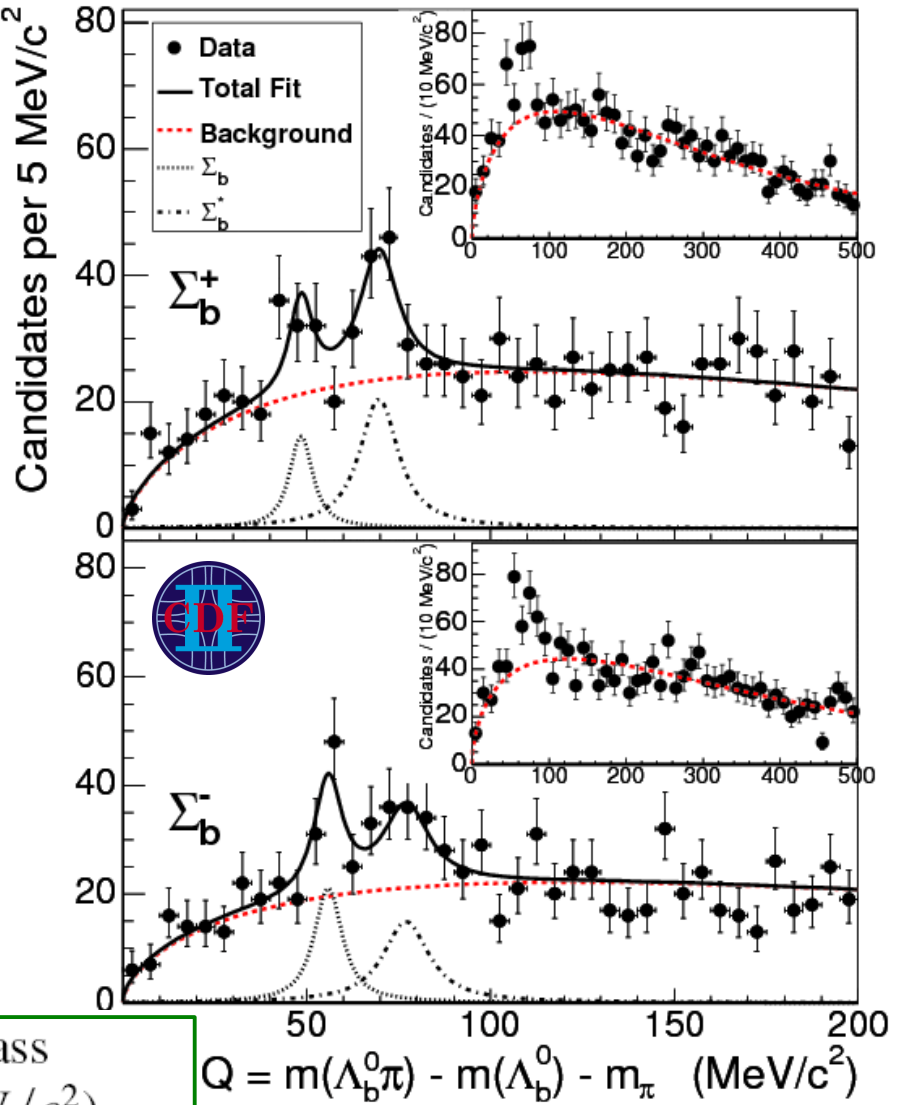
Observed by CDF in 2007:

Use two-track trigger to reconstruct

$$\Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0 \, \pi^\pm$$
$$\hookrightarrow \Lambda_c^+ \pi^-$$
$$\hookrightarrow pK^-\pi^+$$

Use large sample of ~3000 Λ_b:

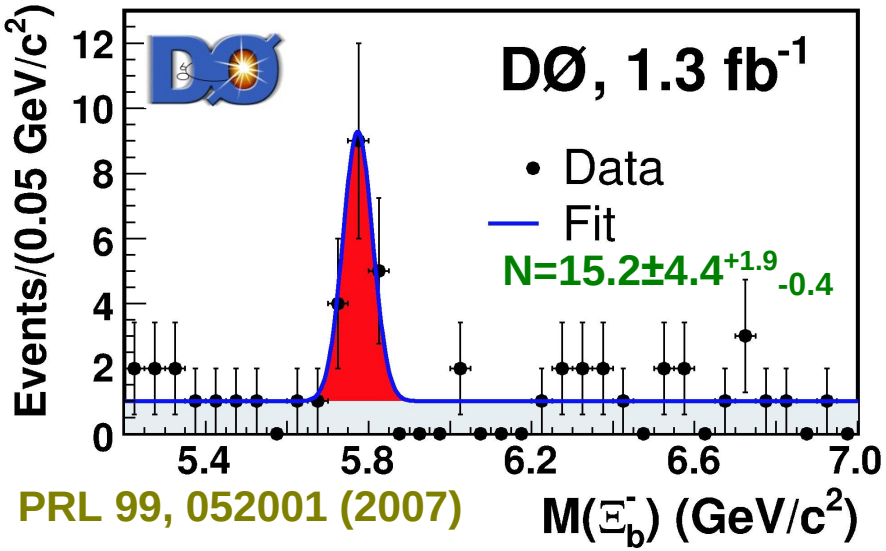
Observe peaks with >5σ w.r.t. no signal



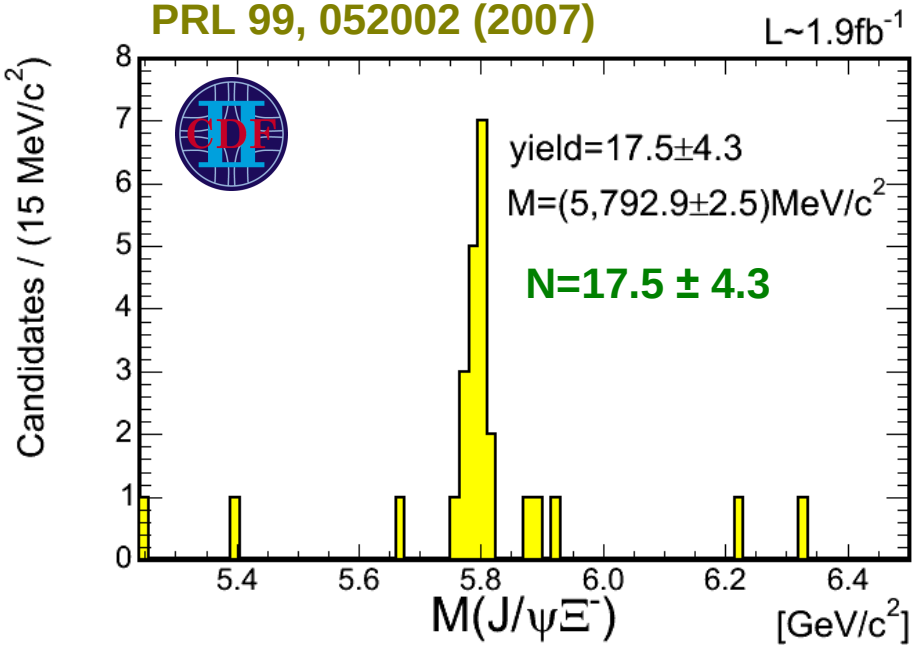
State	Yield	Q or $\Delta_{\Sigma_b^*}$ (MeV/c^2)	Mass (MeV/c^2)
Σ_b^+	32^{+13+5}_{-12-3}	$Q_{\Sigma_b^+} = 48.5^{+2.0+0.2}_{-2.2-0.3}$	$5807.8^{+2.0}_{-2.2} \pm 1.7$
Σ_b^-	59^{+15+9}_{-14-4}	$Q_{\Sigma_b^-} = 55.9 \pm 1.0 \pm 0.2$	$5815.2 \pm 1.0 \pm 1.7$
Σ_b^{*+}	77^{+17+10}_{-16-6}	$\Delta_{\Sigma_b^*} = 21.2^{+2.0+0.4}_{-1.9-0.3}$	$5829.0^{+1.6+1.7}_{-1.8-1.8}$
Σ_b^{*-}	69^{+18+16}_{-17-5}		$5836.4 \pm 2.0^{+1.8}_{-1.7}$

PRL 99, 202001 (2007)

Ξ_b Baryon

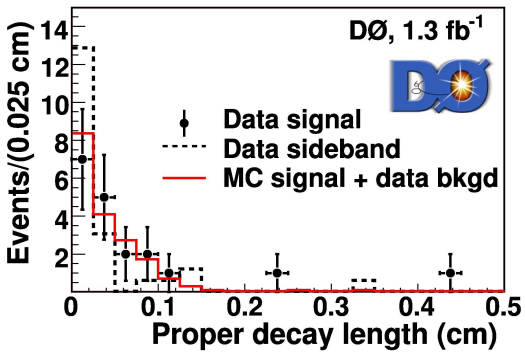


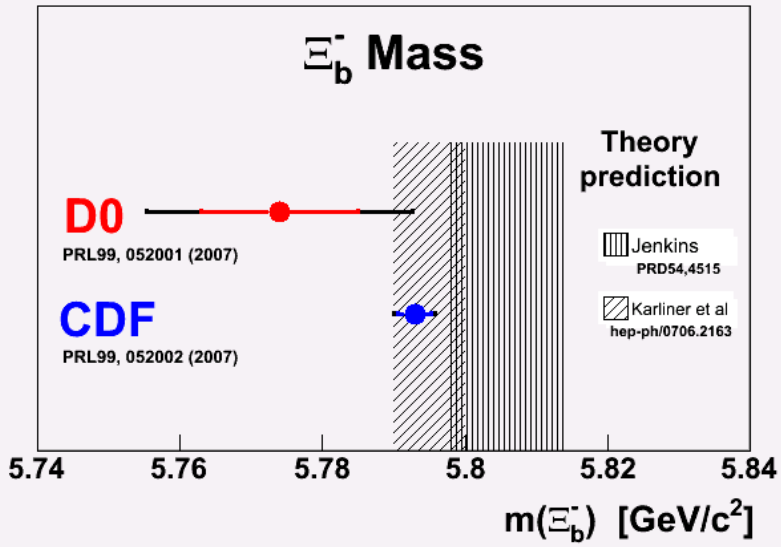
PRL 99, 052001 (2007)



Both experiments see significant Ξ_b signals (D0: 5.5σ, CDF: 7.7σ)

- **CDF: $m(\Xi_b) = (5792.9 \pm 2.5 \pm 1.7)$ MeV/c²**
- **D0: $m(\Xi_b) = (5774 \pm 11 \pm 15)$ MeV/c²**
- **World avg: $M(\Xi_b) = 5792.4 \pm 3.0$ MeV/c²**
- **D0: Lifetime consistent with expectations**

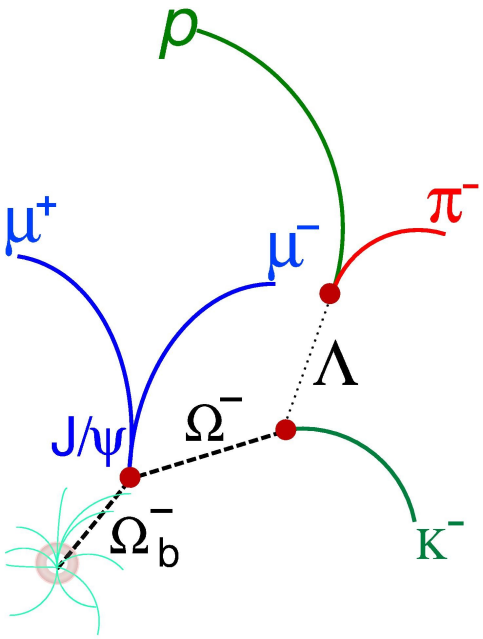




Ω_b Baryon

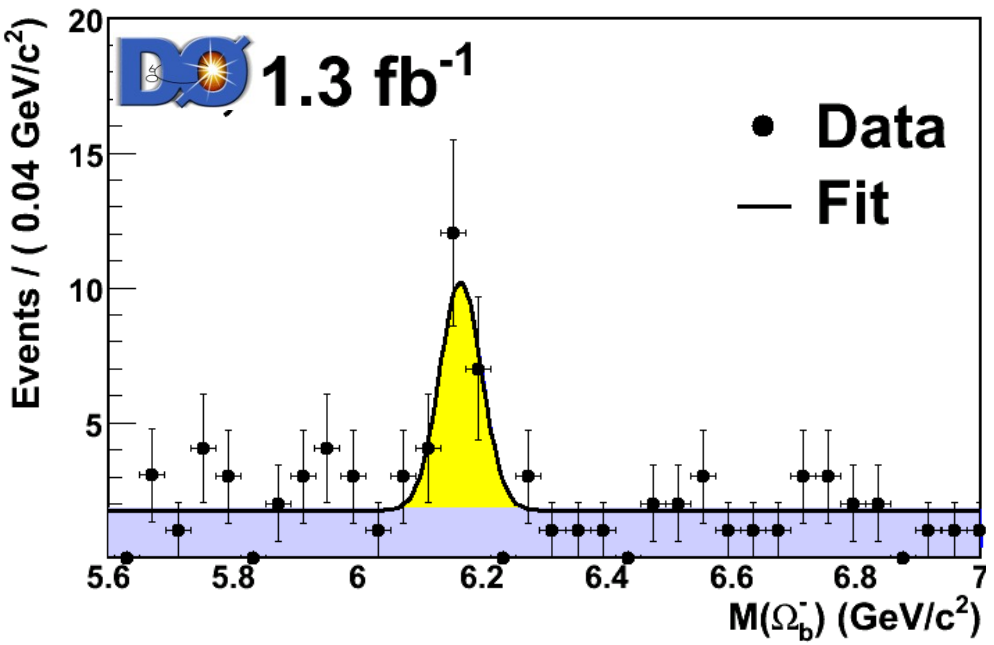
- **Observation by D0 in Aug'08 with 1.3 fb^{-1} data (Builds on previous observation of Ξ_b)**
- **Observe 17.8 ± 4.9 ± 0.8 events**
- **Report signal significance: 5.4σ**
- **m(Ω_b) = (6165 ± 10 ± 13) MeV/c^2**

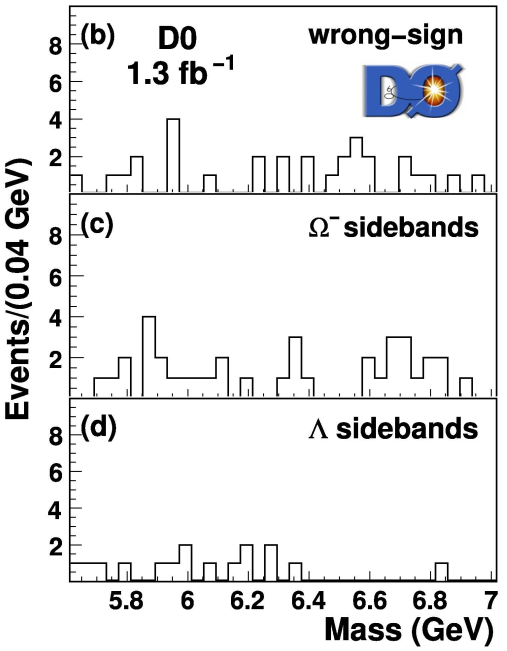
(expect 5.94-6.12 GeV/c^2)



- $$\frac{f(b\to\Omega_b^-)B(\Omega_b^-\to J/\psi\Omega^-)}{f(b\to\Xi_b^-)B(\Xi_b^-\to J/\psi\Xi^-)}=0.80\pm0.32^{+0.14}_{-0.22}$$

PRL 99, 052001 (2007)





Ω_b Baryon

NEW!

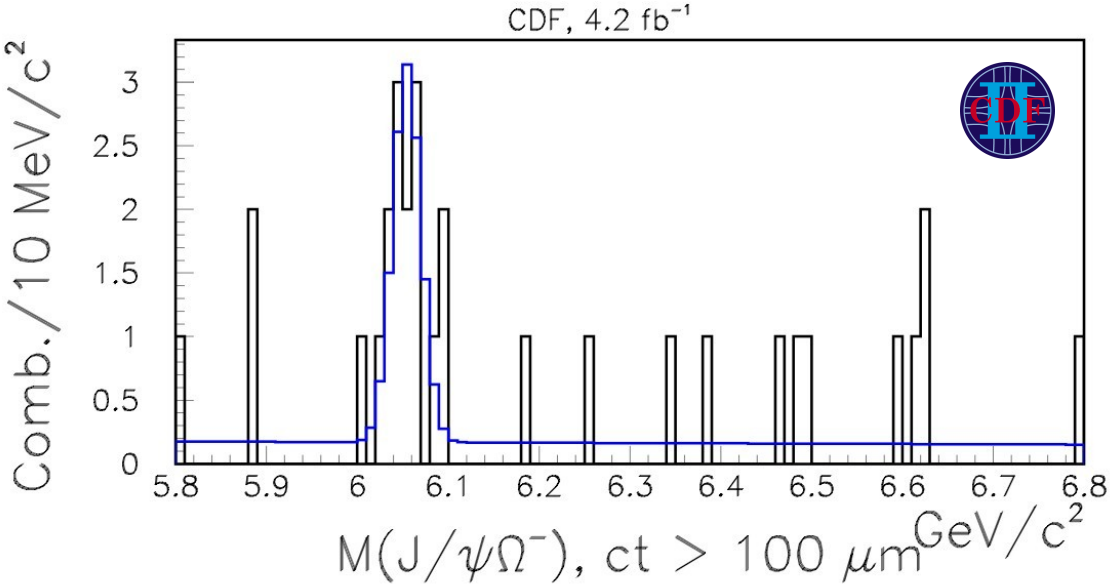
- **Comprehensive reconstruction of bottom baryons into J/ψ**

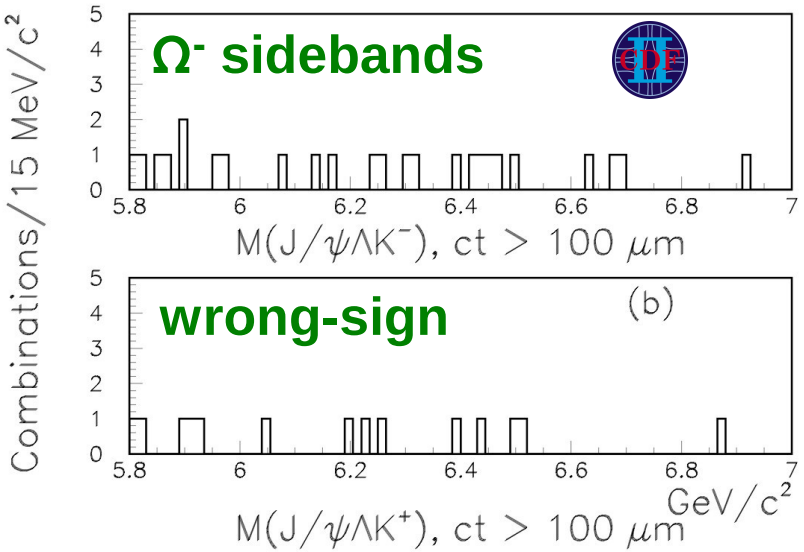
$$\Lambda_b^0 \to J/\psi\,\Lambda; \quad \Lambda \to p\pi^-; \quad J/\psi \to \mu^+\mu^-$$
$$\Xi_b^- \to J/\psi\,\Xi^-; \quad \Xi^- \to \Lambda\pi^-$$
$$\Omega_b^- \to J/\psi\,\Omega^-; \quad \Omega^- \to \Lambda K^-$$

- **Measurement of B^0 properties provides cross check:**

$$B^0 \to J/\psi\,K^{*0} \quad \& \quad B^0 \to J/\psi\,K_S^0$$

- **Observe structure of 16 signal events in J/ψ Ω with 5.5σ signif.**



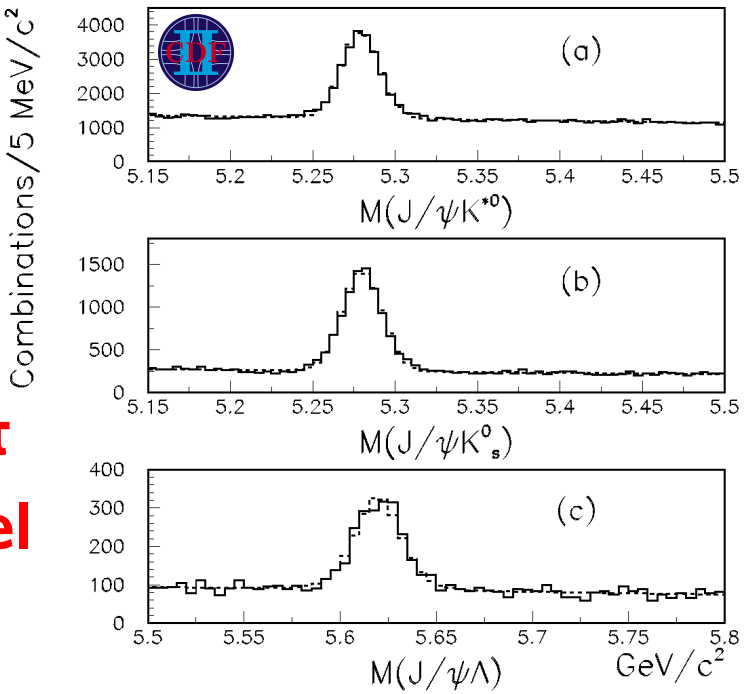


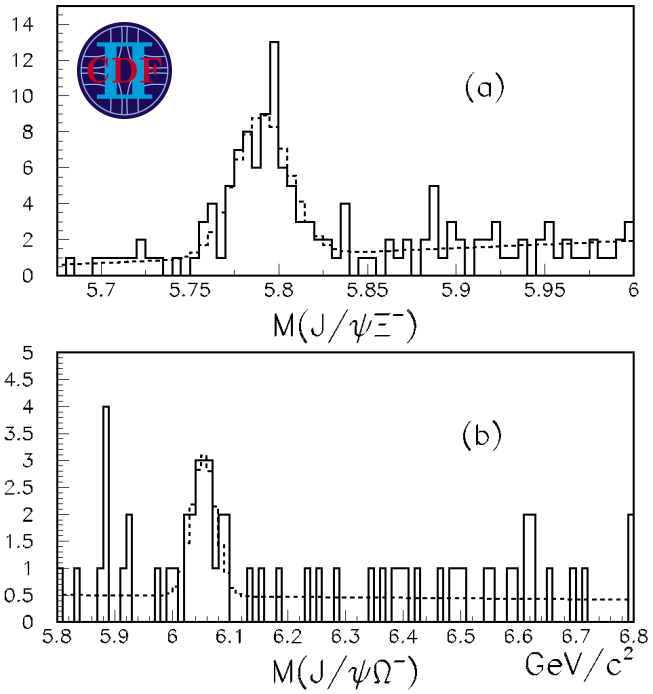
Ω_b Baryon

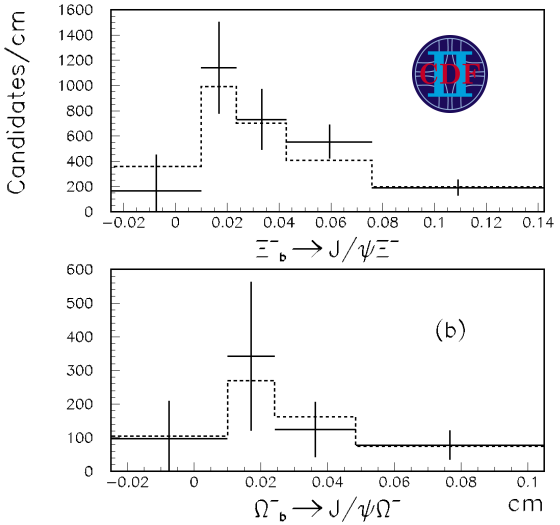
NEW!

arXiv:0905.3123 [hep-ex]

- Masses from fit to sample with $c\tau > 100\ \mu m$
- Lifetime from yield in bins of $c\tau$ (no need to model background)







Resonance	Yield	$c\tau$ [μm]	Mass [MeV/c^2]
$B^0(J/\psi\, K^{*0})$	17250 ± 305	453 ± 6	5279.2 ± 0.2
$B^0(J/\psi\, K^0_S)$	9424 ± 167	448 ± 7	5280.2 ± 0.2
Λ_b^0	1934 ± 93	472 ± 17	5620.3 ± 0.5
Ξ_b^-	66^{+14}_{-9}	468^{+82}_{-74}	5790.9 ± 2.6
Ω_b^-	16^{+6}_{-4}	340^{+160}_{-120}	6054.4 ± 6.8

Ω_b Baryon

NEW!

- **CDF observes Ω_b Baryon**
- **Relative rate measurement (assume kinematics identical to Λ_b)**

$$\frac{\sigma B(\Xi_b^- \to J/\psi \Xi^-)}{\sigma B(\Lambda_b^0 \to J/\psi \Lambda)} = 0.167^{+0.037}_{-0.025}(stat.) \pm 0.012(syst.)$$

$$\frac{\sigma B(\Omega_b^- \to J/\psi \Omega^-)}{\sigma B(\Lambda_b^0 \to J/\psi \Lambda)} = 0.045^{+0.017}_{-0.012}(stat.) \pm 0.004(syst.)$$

- **Summary of mass measurement**

$$m(\Xi_b^-) = (5790.9 \pm 2.6 \pm 0.9)\ \mathrm{MeV}/c^2$$
$$m(\Omega_b^-) = (6054.4 \pm 6.8 \pm 0.9)\ \mathrm{MeV}/c^2$$

- **Summary of lifetime measurement**

$$\tau(\Xi_b^-) = (1.56^{+0.27}_{-0.25} \pm 0.02)\ \mathrm{ps}$$ **<-- First fully rec.**

$$\tau(\Omega_b^-) = (1.13^{+0.53}_{-0.40} \pm 0.02)\ \mathrm{ps}$$ **<-- First !**

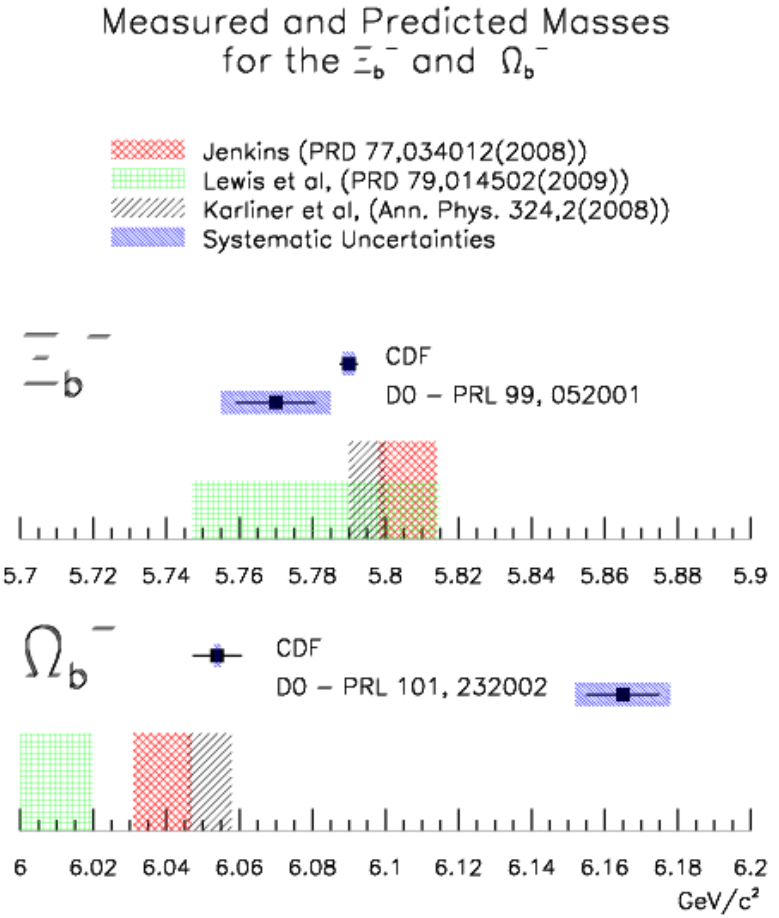
Ω_b Baryon

Comparison with D0 result:

- D0: $m(\Omega_b) = (6165 \pm 10 \pm 13)$ MeV/c^2

  => $\Delta m = (111 \pm 12 \pm 14)$ MeV/c^2

Significant disagreement !



Rate measurements:

D0: $$\frac{f(b \to \Omega_b^-) B(\Omega_b^- \to J/\psi \Omega^-)}{f(b \to \Xi_b^-) B(\Xi_b^- \to J/\psi \Xi^-)} = 0.80 \pm 0.32^{+0.14}_{-0.22}$$

CDF: $$\frac{\sigma B(\Omega_b^- \to J/\psi \Omega^-)}{\sigma B(\Xi_b^- \to J/\psi \Xi^-)} = 0.27 \pm 0.12 \pm 0.01$$

In agreement ?

Conclusions

- Tevatron offers rich heavy flavour program
- Many result from B_s mesons and bottom baryons:
  - CP violation in B_s^0 -> $J/\psi\ \phi$ remains interesting
  - Heavy baryons Σ_b, Ξ_b established
  - Discovery of Ω_b => Discrepancy between CDF & D0
- Tevatron accumulates more data until end of Run II
  => Expect more results
  from CDF & D0